EXPERIMENTAL STUDIES ON SEDIMENTATION MECHANISM AND SEDIMENT FORMATION OF CLAY MATERIALS

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ABSTRACT

Sedimentation mechanism and sediment formation characteristics are examined by use of dilute clay-water mixtures. Direct measurement of the distribution of water content in the mixture is successfully used in the examination. According to the results, the process of soil sedimentation in general comprises three stages.

In the first stage, no settling takes place, but flocculation yields flocs. In the second stage, the flocs gradually settle and form a layer of sediment, which undergoes consolidation and reduction of water content. The boundary between the upper settling zone and the sediment is the birth place of new sediment. While the sediment grows, the settling zone becomes thinner and finally vanishes. In the last stage, all of the sediment thus formed undergoes self-weight consolidation and finally approaches an equilibrium state.

The water content value at which a mixture changes into sediment is not uniquely determined, but varies corresponding to the mixture's initial water content; the two values are close to each other. That is, soil sediment is not formed at a water content peculiar to the material concerned. This remarkable finding is a reflection of the fact that, even for a clay, countless compression curves exist under very low effective stresses.

Key words: clay, consolidation, sedimentation, water content

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INTRODUCTION

Most soil layers are formed in water areas through the process of sedimentation. The soil particles suspended in water will settle under the action of gravitational force and form a layer of soil sediment at the surface of the underlying sediment. The sediment thus formed will be further consolidated by the weight of the overlying sediment. That is, the process of sedimentation intrinsically comprises three different phenomena: settling, sediment formation and consolidation.

Studies on the sedimentation mechanism, therefore, should premise a common concept about the conditions under which a group of soil particles changes into a mass of sediment. Although the conditions are difficult to clearly state, the following concept is

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accepted: a mass of sediment is formed when soil particles settled onto the bed sediment begin to interact with each other and form an aggregate which transmits an effective stress by virtue of particle-to-particle contacts. Based on this definition, Monte and Krizek (1976) proposed a concept of limiting water content termed "fluid limit". When the water content of a soil-water system decreases to the fluid limit, the system changes into a soil mass. Therefore, a system having a water content value higher than the fluid limit is in a stress-free state, and consolidation theories can be applied only from the moment at which the system changes into a soil mass.

Kynch developed an excellent theory for hindered settling, in which free settling of particles is interrupted by their mutual collisions, and the particles settle in the aggregate (1952). He assumed that the aggregate of settled particles never consolidates, and gave an illustrative mechanism for hindered settling as shown in Fig. 1. This provides a clear-cut idea of the interrelation between settling and sediment formation. Uniformly dispersed particles settle in the aggregate forming a sharp interface between the dispersion and clear water. When a group of particles reaches the surface of the underlying sediment, it changes into a soil mass, abruptly decreasing its water content to a certain value. That is, new sediment is formed at the boundary between the dispersion and sediment. As is shown in Fig. 1, this boundary moves, tracing a "sediment formation line". The uniform settling of particles and the lack of consolidation in the sediment makes it a straight line.

Kynch further analyzed the characteristics of hindered settling based on the assumption that the settling velocity of particles depends only on their local concentration. Any slight disturbance of the concentration is propagated within the dispersion. Such propagation lines correspond to a kind of constant water content line. According to Kynch's theory, they are straight, as shown in Fig. 2, and parallel if the dispersion is uniform. They intersect with and vanish on two straight discontinuity lines; one is the interface and the other is the sediment formation line. On the former line the water content values abruptly change to infinity, and on the latter line they change into a definite value peculiar to the sediment. Within the zone below the sediment formation line no constant water content line can be drawn because that zone undergoes no consolidation and is uniform. To take account of the consolidation effect, which can never be neglected in fine materials, McRoberts and Nixon (1976) further advanced Kynch's theory. But their results may indicate that a theory such as Kynch's is too simple to treat sophisticated phenomena of clay sedimentation.

On the other hand, Mikasa (1963) mathematically interpreted the mechanism of settling based on his self-weight consolidation theory for very soft clay. Considering

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**Fig. 1.** Idealized characteristics of hindered settling

**Fig. 2.** Settling mode expressed by constant water content lines; (a) thin dispersion, and (b) thick dispersion
uniform and very soft clay in a container, he assumed that no strain occurred in the upper zone, while consolidation proceeds within the lower zone. In this situation, the submerged unit weight of soil aggregate in the upper zone $\gamma'$ balances with the upward seepage force caused by the water squeezed from the lower zone, and the soil aggregate settles at a rate $v$ expressed as follows:

$$v = k\frac{\gamma'}{\gamma_w}$$  \hspace{1cm} (1)

where $k$ is the permeability coefficient of the aggregate settling, and $\gamma_w$ is the unit weight of water. Because no strain takes place, both $k$ and $\gamma'$ maintain their initial values. Therefore, the settling rate is constant; i.e., an interface traces a straight line on the time-space plane.

While Kynch's theory gives a clear-cut concept of sediment formation, it is not adequate to treat consolidation. Mikasa's theory, on the other hand, satisfactorily interprets the settling mechanism as a particular case of self-weight consolidation, but it can give no information regarding sediment formation. That is, both theories are unsatisfactory to successfully interpret the whole aspect of sedimentation phenomena which comprises settling, sediment formation and consolidation. Experimental investigations should be rather strengthened to have a deep insight into the sedimentation mechanism. This is the main subject of the present study.

To examine the sedimentation mechanism, it is required to measure the distribution of water content in a mixture and its variation with time. Such a trial by Gaudin and Fuerstenau (1958) with use of a X-ray transviewer successfully provided indirect measurements of the density distributions in mixtures. In the present study, however, a more simpler device was developed; it cuts a mixture into slices and provided direct measurements of the water content distribution. By the aid of this device, advanced understandings about the interrelationships between settling, sediment formation and consolidation, and about the conditions of the sediment formation were obtained.

**EXPERIMENTAL PROCEDURE**

Four kinds of clayey soil were used in this study. Dilute soil-water mixtures prepared from them were allowed to settle in sedimentation tubes, then water content distribution in the mixture was directly measured.

**Settling Type Studied**

Four different settling types are in general observed for a clay-water mixture (Imai, 1980). "Dispersed free settling" is observed when both the mixture's solid concentration and the water's salt concentration are low; dispersed soil particles settle freely. "Flocculated free settling" takes place when solid concentration is low but salt concentration is high; soil particles flocculate into flocs, which settle freely. "Zone settling" occurs when solid concentration is higher than in the case of flocculated free settling; flocs settle in the aggregate forming a sharp interface. This type of settling is the same as the hindered settling treated by Kynch. "Consolidation settling" is always observed under high solid concentration independently of salt concentration.

As the present study confines its interest to the sedimentation phenomena taking place in sea water areas, dispersed free settling is not covered by this study. It further focuses its scope on the sedimentation of thick dispersions, which occurs in hydraulic land-filling work, therefore, flocculated free settling may also be disregarded. In the present study, therefore, zone settling and consolidation settling are examined.
Materials Tested and Preparation of Mixtures

Three kinds of bay mud were collected from three bays in Japan and used in this study. Their index properties and grain size distribution are listed in Table 1. Their colloidal fraction reaches about 40 to 50 percent, and they show high plasticity. For comparison, kaolin powder was also used. Its plasticity is so low that it is expected to behave like a sandy material. Natural sea water samples from Yokohama Port were used to prepare dilute soil-water mixtures. Because the mixture thus prepared contain much salt, their water content values should be corrected to take account of salinity. Every water content value \( w_m \) determined through the traditional oven-drying method was corrected by using the following equation:

\[
w = \frac{w_m}{1 - (S/S_w)(1 + w_m)}
\]

where \( S \) is salt concentration, which is defined by the weight of salt crystallized from a unit volume of water. Based on Eq. (2), the weights of bay mud and sea water necessary to prepare a mixture of predetermined volume and water content were calculated (Imai, 1979).

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Specific Gravity (%)</th>
<th>Plastic Limit (%)</th>
<th>Liquid Limit (%)</th>
<th>Plasticity Index (%)</th>
<th>Grain Size Distribution (weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Sendai Bay mud</td>
<td>2.651</td>
<td>32</td>
<td>126</td>
<td>94</td>
<td>40</td>
</tr>
<tr>
<td>2.</td>
<td>Ohsaka Bay mud</td>
<td>2.703</td>
<td>31</td>
<td>101</td>
<td>70</td>
<td>47</td>
</tr>
<tr>
<td>3.</td>
<td>Tokyo Bay mud</td>
<td>2.669</td>
<td>38</td>
<td>105</td>
<td>67</td>
<td>46</td>
</tr>
<tr>
<td>4.</td>
<td>kaolin</td>
<td>2.673</td>
<td>30</td>
<td>45</td>
<td>15</td>
<td>40</td>
</tr>
</tbody>
</table>

Sedimentation Tube

Transparent unit sedimentation tubes, 25 cm in height and 5 cm in inside diameter, were used. Each has flange plates at both ends, by which they can be joined to construct a sedimentation tube of the required height. A piston is inserted at the bottom of the tube thus constructed to maintain a no drainage condition. Another type of large unit sedimentation tubes, 20 cm in inside diameter and 25 cm in height, was used for special tests.

Measurement of Water Content Distribution

To directly measure the vertical distribution of water content for a soil-water mixture in a sedimentation tube, the special apparatus shown in Fig. 3 was developed. A sedimentation tube is first fixed on the gear box, which can be run up and down the screwed support by turning the handle. Then the cutter base shown in Fig. 3(b) is fixed on the upper flange of the sedimentation tube, and the cutter is set on the base. When the gear box is lowered, the piston in the sedimentation tube is pushed up relatively to the tube, raising the mixture in the tube as a whole until its top enters the cutter tube. The cutter is slid along its base, cutting off a slice which falls into a container through the hole near the end of the cutter base. By repeating this one-cycle operation the whole mixture can be cut into slices of optional thickness. The water content values measured for these slices yield the water content distribution in the mixture.

One cycle of the cutting operation inevitably requires a finite time \( \Delta t \), during which settling of soil particles occurs in the next slice to be cut. When the rate of settling is \( v \), a water layer of \( v \cdot \Delta t \) depth is consequently formed as shown in Fig. 4. This results in overestimation of the water content value. Assuming uniform settling, the
correct value $w$ is related to the measured value $w_a$ as follows:

$$\frac{\Delta z - v \cdot \Delta t}{1 + (G_d/G_w)w} = \frac{\Delta z}{1 + (G_d/G_w)w_a}$$

(3)

where $G_d$ and $G_w$ are the specific gravity of soil particles and water, respectively, and $\Delta z$ is the thickness of slice. When a mixture is cut into uniform thickness at uniform time intervals, then the cutting rate $v_c$ can be defined as $\Delta z/\Delta t$. In this case, Eq. (3) is rewritten as

$$\frac{w_a}{w} = \frac{(v_c/v) + (G_d/G_w)w}{(v_c/v) - 1}$$

(4)

Fig. 4 shows the effect of the ratio $v_c/v$ on the ratio $w_a/w$. As settling rate decreases and/or cutting rate increases, the measured water content approaches the correct one. The chart in Fig. 4 is convenient for the correction of measurements.

EXAMINATION OF GRAIN-SIZE SORTING DURING SETTLING

If grain-size sorting occurs during settling, the meaning of examining the distribution of water content may be lost because the nature of the mixture itself is no longer uniform. This grain-size sorting may be more remarkable as mixture's initial height and/or the initial water content increase. Therefore, to perform the present study under conditions of negligible sorting, these two quantities must be subject to some restriction.

Test Procedure

Two series of sorting tests were run; i.e., in one series the degrees of grain-size sorting were directly measured, and in the other series its effect on the water content properties of the sediment formed through sedimentation was examined. A mixture of 1000 percent water content was prepared by use of Tokyo Bay mud and sea water. In the former series, it was poured into two large sedimentation tubes. The initial height of the mixture was 100 cm in one tube and 200 cm in the other. After the completion of self-weight consolidation several soil masses were sampled from the sediment, and grain size analyses were performed on them. The results of this series are shown in Fig. 5(a).

In the latter series, the mixture was poured into four small sedimentation tubes; the
initial height of the mixture was 25, 50, 100 and 200 cm, respectively. After the completion of self-weight consolidation the distribution of water content was determined for each sediment. The relationship between the water content and effective stress was then determined by the method described later. The results of this series are shown in Fig. 5(b). All of the mixtures exhibited typical zone settling.

Test Results

Fig. 5(a) clearly shows that the particles coarser than 74 μm are uniformly distributed over the whole sediment. They underwent very little grain-size sorting because by the time settling started they had been confined in flocs. On the other hand, considerable sorting took place for the particles finer than 74 μm. This sorting occurred to a marked degree in the case of 200 cm height, but was not so marked in the 100 cm case. This sorting of finer particles must reflect on the compression curve of the sediment. Fig. 5(b) does show a remarkable discrepancy among compression curves. It should be noted, however, that the discrepancy between the 50 cm case and the 25 cm case is almost negligible. That is, grain-size sorting may be negligible when the mixture's initial height is lower than 50 cm. However, if the mixture's initial water content is higher than the present case of 1000 percent, this limiting height may be lower than 50 cm. In the present study, therefore, the initial mixture's height will be limited to about 25 cm.

WATER CONTENT DISTRIBUTION AND ITS CHANGE WITH TIME

Test Procedure

The distribution of water content in mixtures and its variation with time were examined for kaolin and Ohsaka Bay mud. The mixture's initial water content was adjusted to 700 percent for kaolin and 2000 percent for Ohsaka Bay mud to examine the case of typical zone settling. At first the mixture was poured into several small unit sedimentation tubes to a uniform initial height: 21.5 cm for kaolin and 23.5 cm for
Fig. 6. The distribution of water content in a mixture and its variation with time (kaolin)

Fig. 7. The distribution of water content in a mixture and its variation with time (Ohsaka Bay mud)

Ohsaka Bay mud. Each mixture was then stirred thoroughly and allowed to settle. At predetermined time intervals each mixture was cut into slices, and its water content distribution was determined.

Figs. 6(a) and 7(a) show the sedimentation curve and the traces of slice cutting expressed by broken lines. The cutting rate \( v \) was a uniform 5 cm/min. In the case of Ohsaka Bay mud, for example, the settling rate of the interface \( \nu \) was 0.25 cm/min during the settling stage, and less than 0.05 cm/min during the succeeding consolidation stage. The ratio \( \nu / \nu \) was therefore 20 in the settling stage and more than 100 in the consolidation stage. According to the chart of Fig. 4, the corresponding ratio \( \nu / \nu \) was 1.05 and lower than 1.005, respectively. That is, correction of the measured water content was necessary only for the settling stage, and only for slices not yet consolidated. Figs. 6(b) and 7(b) show the distribution curves of water content thus obtained.
Water Content Distribution in the Flocculation Stage

In typical zone settling, the whole sedimentation process is in general divided into three stages as shown in Fig.7(a); i.e., flocculation, settling and consolidation (Imai, 1980). In the case of kaolin, however, no obvious flocculation stage could be recognized because flocculation took place quite rapidly. In the case of Ohsaka Bay mud, on the other hand, the early eight minutes were the flocculation stage, during which the soil particles were first dispersed in the mixture exhibiting no settling, but soon flocculated into flocs in a short time. During this stage, therefore, water content of the mixture should be unaltered at any local area. This situation is clearly shown by the distribution curve ① in Fig.7(b). The mixture is exceedingly uniform and maintains its initial water content.

Water Content Distribution in the Settling Stage

When flocculation finishes at every local area in the mixture, the permeability of the whole mixture abruptly increases and the flocs start to settle in the aggregate. The uniformity of the mixture is then disturbed as shown in the distribution curves ② to ④ for kaolin and ② and ③ for Ohsaka Bay mud. Water content increases in the upper zone and decreases in the lower zone. The decrease in water content in the lower zone evidently results from the consolidation caused by the self-weight of sediment. The increase in water content in the upper zone, on the other hand, indicates that the aggregate of flocs has not yet undergone consolidation and is still settling. The boundary between these two zones, expressed by a turning point on the distribution curve, should be considered as the birth place of new sediment. The zone above the boundary is here called the “settling zone”, and the zone below is the “consolidation zone”. The boundary moves upward as settling proceeds because the successive formation of new sediment takes place at the boundary. That is, the addition of a new sediment layer increases the thickness of the consolidation zone while conversely reducing that of the settling zone. Therefore, the settling zone inevitably vanishes at some time, and at that time the settling stage ends. Water content distribution in this situation is shown by the curve ⑤ for kaolin and ⑥ for Ohsaka Bay mud.

Water Content Distribution in the Consolidation Stage

At the end of the settling stage there are no flocs still settling, and a mass of soil sediment is formed. After that time the whole sediment undergoes self-weight consolidation. Every element of the sediment gradually decreases its water content, as shown by the curve ⑦ for kaolin and ⑧ for Ohsaka Bay mud, and the sediment finally approaches an equilibrium state, which is shown by the curve ⑨ for kaolin and ⑩ for Ohsaka Bay mud.

It should be mentioned here that the water content near the top surface of the sediment decreases remarkably during this stage. This means an increase in effective stresses acting there. Early in the consolidation stage, the self-weight of the soil aggregate near the top surface is compensated by the upward seepage force induced by the flow of water squeezed from the underlying sediment. In this situation, the effective stress acting near the surface is virtually zero, and the loose fabric of soil aggregate remains near the surface. As consolidation proceeds and the seepage force becomes weak, the self-weight gradually turns into an effective stress. This increasing stress may first destroy the loose aggregate of flocs and then compress the flocs themselves.
CONSTANT WATER CONTENT LINES AND SEDIMENTATION CHARACTERISTICS

Test Procedure

The sedimentation mechanism may be successfully examined by studying the constant water content lines as Kynch did. They can be drawn based on the data of water content distribution and its variation with time. Thus, Figs. 6(b) and 7(b) are sufficient for this purpose, but to supplement them another two series of sedimentation tests were conducted. One was carried out on a mixture of kaolin with an initial water content of 1,400 percent, and the other on a mixture of Ohsaka Bay mud with an initial water content of 500 percent. The former mixture exhibited typical zone settling, and the latter typical consolidation settling.

Constant Water Content Lines and Sedimentation Characteristics

The constant water content lines thus obtained are shown in Figs. 8 and 9. In the cases of zone settling (Figs. 8(a), 8(b) and 9(a)) three different zones can be distinguished. One of them is a "flocculation zone", which is found in Ohsaka Bay mud but not in

Fig. 8. Constant water content lines of kaolin mixtures; (a) when \( w_0 = 1,400\% \) (zone settling), and (b) when \( w_0 = 700\% \) (zone settling)

Fig. 9. Constant water content lines of mixtures of Ohsaka Bay mud; (a) when \( w_0 = 2,000\% \) (zone settling), and (b) when \( w_0 = 500\% \) (consolidation settling)
kaolin. This zone dominates the whole area of the mixture until the start of settling. The mixture's initial water content remains within this zone. During the settling stage, however, both a "settling zone" and a "consolidation zone" appear concurrently. The boundary between these two zones is of course a sediment formation line (expressed by a broken line in the figures). The settling zone initially dominates the whole area, but it gradually decreases and vanishes at the end of the settling stage. Conversely, the consolidation zone gradually grows until it dominates the whole sediment at the end of the settling stage. In the succeeding consolidation stage, the consolidation zone alone dominates the whole sediment. The sediment decreases in thickness to finally approach an equilibrium state.

In the case of consolidation settling (Fig. 9(b)), similar sedimentation characteristics should be observed because the fundamental mechanism must be common to both types of settling (Imai, 1980). Although the flocculation zone is clearly seen in Fig. 9(b), no obvious settling zone can be found, probably due to the uniformity of the settling zone and the limited measurement accuracy. The broken line in Fig. 9(h) is the initial water content line. It should be considered as a sediment formation line because the decrease in water content starts from it. The area below that line, therefore, is the consolidation zone, and the area above is the settling zone.

Based on these results, generalized sedimentation characteristics can be illustrated as in Fig. 10. This differs in several points from Fig. 1: i.e., existence of a flocculation zone, non-uniformity of the settling zone, non-linearity of the sediment formation line, non-uniformity of the consolidation zone and volume reduction during the consolidation stage. While Fig. 10 may be a good representation of the sedimentation of clay-water mixtures, Fig. 1 may be more appropriate for sandy materials which exhibit low plasticity and little consolidation.

Examination of the Settling Zone

Mikasa assumed uniformity within the settling zone (1963), but this assumption does not hold good in the case of zone settling, since water content values in the settling zone increase as settling proceeds. This remarkable phenomenon may be interpreted as follows. When incompressible particles as sand uniformly settle onto the surface of the underlying sediment, their aggregate is abruptly decreased in volume, squeezing out water. Because no water is squeezed from the underlying sediment, only the water squeezed from the settled aggregate passes upward through the settling zone. Since its rate is always constant, the seepage flow in the settling zone must be steady and that zone consequently retains its initial uniformity. When compressible soil floccs settle, on the other hand, water is squeezed from the whole area of the underlying sediment. Because its thickness increases, an increasing volume of water must pass through the settling zone, whose thickness is decreasing. Therefore, the upward seepage force acting within the settling zone must increase. This consequently causes an increase in the
average water content within the settling zone. That is, the increase in water content of the settling zone is closely related to the consolidation which proceeds within the consolidation zone.

**Examination of the Sediment Formation Line**

Fig. 8 through 10 show the non-linearity of the sediment formation line. This can also be interpreted as an effect of consolidation. When compressible soil flocs settle onto the surface of underlying sediment, their aggregate consolidates, decreasing in volume. The rate of this volume decrease will always be constant as long as uniform settling takes place. Therefore, if there was no other contribution to the volume decrease, the sediment formation line would be straight. In fact, however, there is an increasing contribution from the growing sediment. Hence, the sediment formation line must curve convexly upward.

**Conditions of Sediment Formation**

According to Kynch's theory the sediment formation line is a discontinuity line as shown in Fig. 2. When an element of dispersion reaches the line, its water content discontinuously changes into a definite value. Therefore, the sediment formation line must be a constant water content line. The same conclusion can be deduced by assuming that the fluid limit (Monte and Krizek, 1976) is a material constant like Atterberg limits. In this case, the water content value on the sediment formation line is uniquely determined for a material.

Figs. 8 and 9 clearly show that the sediment formation line is not a discontinuity line. The water content distribution plotted in Figs. 6(b) and 7(b) also shows no discontinuity. However, if the mixture's water content was still higher than those cases, it might be discontinuous. That is, while the water content in the consolidation zone can never take any value higher than a certain limit, the water content in the settling zone can even approach infinity. Hence, discontinuity of the sediment formation line can be observed only when the mixture's water content is high enough.

On the other hand, Figs. 8 and 9 confirm that the sediment formation line is a constant water content line. At the same time, however, they show clearly that its value is not uniquely determined for a material but is near the mixture's initial one. That is, the fluid limit is not a material constant; it depends on the mixture's initial water content, i.e., on the conditions under which new sediment is formed. From this finding it can be speculated that countless compression curves can exist even for one kind of clay, because the fluid limit is a starting point of consolidation and there are countless starting points. Experimental verifications for this speculation will be presented in the next section.

**COMPRESSION CURVES UNDER VERY LOW EFFECTIVE STRESSES**

**Test Procedure**

To examine the effect of the mixture's initial water content on compression curve, three kinds of clay were used; i.e., Sendai Bay mud, Ohsaka Bay mud and kaolin. From each material mixtures with a wide variety of initial water contents were prepared. They were allowed to settle in small unit sedimentation tubes to obtain the sediments. After each sediment had completely consolidated, its water content distribution was measured by cutting it into slices. To get the correct compression curve, the completion of self-weight consolidation has to be confirmed. Fig. 11 shows a family of sedimentation curves of Ohsaka Bay mud. The rate of volume reduction abruptly slows down at the
were modified by the following relation:

\[
\frac{H}{\bar{H}} = \frac{1 + (G_s/G_w)w_t}{1 + (G_s/G_w)\bar{w}_t}
\]  

(5)

where \( H \) and \( \bar{H} \) are the height of sediment at the time marked by \( \oplus \) and at the time of slicing, respectively, and \( w_t \) is modified water content. By using a value \( w_w \), the submerged unit weight \( \gamma' \) was calculated for each slice by use of the following equation:

\[
\gamma_i' = \frac{(G_s/G_w) - 1}{1 + (G_s/G_w)\bar{w}_t}\gamma_w
\]  

(6)

The vertical effective stress \( \sigma_{i}' \) acting on the center plane of the \( i \)th slice was then determined by the following equation:

\[
\sigma_{i}' = \sum_{j=1}^{i-1} \gamma_{j}' \cdot \Delta z_{j} + \frac{1}{2} \gamma_{i}' \cdot \Delta z_{i}
\]  

(7)

The \( n \)-sets of the pair \((w_w, \log \sigma_{i}')\) thus obtained yield a compression curve of the sediment which finished 100 percent primary consolidation and was situated on the point marked by \( \oplus \) in Fig.11.

Compression Curve and Fluid Limit

The compression curves thus obtained are shown in Fig.12. The data presented there, except those for kaolin, clearly show that the compression curve is not uniquely determined and depends on the mixture’s water content. The data further show that the discrepancy between any two compression curves increases with decreasing effective stress. If an effective stress even lower than the present case could be measured, we could most probably find an even greater discrepancy. This is also supported by the finding that the water content value at zero effective stress, i.e., the value on the sediment formation line, is near the mixture’s water content and is far larger than the maximum value found in Fig.12. From these results it can be concluded that the fluid limit cannot be a material constant but must be a function of the mixture’s water content.

Compression Curve and Settling Characteristics

Although there are countless compression curves, there must be an upper-bound curve enveloping them. This is justified by the fact that no soil aggregate is able to have an infinite water content value. Fig.12 shows that every compression curve may approach
this upper-bound curve as effective stress increases. This approach may be a reflection of changes in the soil fabric. That is, the fabric initially formed on the sediment formation line can vary widely corresponding to the differences in water content, but the difference in the fabric may become less remarkable with increasing stress, and the fabric may be equalized. The stronger the particle-to-particle bonding, the higher the effective stress which equalizes the fabric. According to the results shown in Fig.12, that bonding strength is far weaker for kaolin than for the natural bay mud. In the case of kaolin, therefore, the rate of water content decrease associated with sediment formation is much more remarkable than in the case of natural bay mud (Figs. 6 through 9). An inactive material such as kaolin behaves as a sandy material, and its sedimentation characteristic is near the one shown in Fig.1, especially in the case of a high water content. The higher the plasticity of a material, the more remarkable the distinctive features illustrated in Fig.10.

CONCLUSIONS

From the results of this work, the following conclusions can be drawn:

1) The sedimentation process of a dilute clay-water mixture is in general divided into three stages: flocculation, settling and consolidation.

2) During the flocculation stage, only flocculation of soil particles occurs, maintaining the initial uniformity of water content.

3) In the settling stage, two different zones coexist in a mixture. In the upper settling zone, soil flocs settle through water. The water content in this zone gradually increases because of the consolidation within the lower consolidation zone.

4) The boundary between the two zones is the sediment formation line on which
new sediment is formed from the clay-water mixture. It moves upward, tracing a convex line.
5) At the end of the settling stage the settling zone vanishes. The whole sediment thereafter undergoes consolidation.
6) The sediment formation line is a constant water content line. Its value is not uniquely determined but is very near the mixture’s initial water content; that is, the fluid limit is not a material constant.
7) The finding in 6) is a reflection of the fact that there are countless compression curves even for one kind of clay under very low effective stresses.

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REFERENCES


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